Reliable, Low Mass, Non-Invasive Pressure Transducers

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Abstract

Mass is a major driver for future spacecraft and missions exposed to high radiation levels (i.e. Europa Orbiter) present even more challenge. A variety of non-invasive measurement techniques are in development that enables determination of pressures within a propulsion network. The techniques also have broad appeal for a number of terrestrial pressure measurement applications.

The feasibility of low cost, extremely low mass, robust and non-invasive pressure transducers capable of 0.25% error bands have been demonstrated for tube sizes of 0.25, 0.375, and 0.5 inch diameter. This paper presents progress in the application of several sensor technologies to measure the change of pressure within tubes while minimizing any responses to axial, bending, or torsional loading. A new class of optically excited nanostrain gage and three piezo-resistive transduction based methods will be discussed and their performance compared.

Background

Conventional flight pressure transducers for spacecraft (S/C) applications typically weigh over 0.25 kg (i.e. Cassini units - Figure 1), cost $10-20k per unit plus $50-100K of non-recurring costs, have lead times of 9-12 months, exhibit reliability problems of both long-term drift and zero shift, and their electronic parts are susceptible to radiation induced failures.

While strain gages have been used for years to measure pressure within pressurized systems, the only known application of strain gage technology for spacecraft pressure measurements is their use on external flat surfaces of batteries. In this study internal system pressure is measured by sensing changes in the strain of the tubing outer wall. Such 'hoop strain' measurements offers the advantage over a typical pressure transducer that no penetration of the feed system tubing is required. This alone represents about 95% reduction in system mass with further savings from the elimination of journals and fittings (i.e. tubing welded together). With the emphasis of future S/C clearly headed in the direction of Faster/Better/Cheaper, there is a real window of opportunity for a micro technology alternative to the conventional pressure transducer.

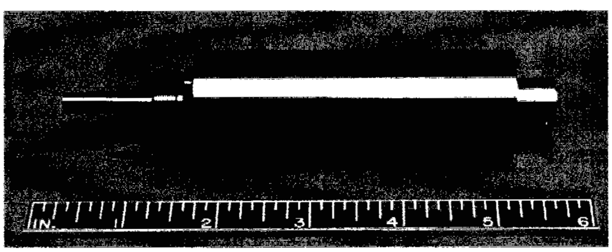

Figure 1. Cassini S/C 0-450 PSIA Pressure Transducer

The two micro strain gage applications are investigated: 1) where conventional foil gages are applied to the outside wall of the feed system tubing wall with adhesives and where piezo resistive gages are sputtered directly onto the tubing wall, and 2) a fiber-optic technique, where an optically excited resonant microbeam nanostrain gage is eutectically bonded to the tubing wall.

Traditionally radiation susceptibility is ameliorated by either a strenuous parts screening program, which translates into additional cost, or the addition of radiation shielding, which translates into additional mass. In the 'hoop strain' implementation there is no 'incorporated' electronics requiring shielding while the opto-resonant microbeams are both electronically inert and impervious to cosmic radiation.

Detailed Approach

Micro-strain gages and optical resonant micro-beam technologies are both considered mature technologies. The primary emphasis is in developing techniques for the intimate bonding of these micro-devices to the circumference of tubes. With intimate bonding, hoop strain sensing will provide non-invasive measurements of pressure differences between the inside and outside of tube. To increase accuracy, temperature measurements will be taken to compensate for any thermal disparities, and individual calibrations of each assembly will accommodate any discontinuities in wall thickness and material properties.

The questions to be answered in this relatively new approach are: 1) how difficult is the application process to the outer tubing wall, especially with smaller tube diameters representative of future generation S/C applications, and 2) how rugged is the installation process, taking into account normal handling loads, and S/C environmental loads (both on the ground and in flight)?

Pressure sensing by measuring strain in tubing outer wall is investigated for piezoresistive and fiber optic techniques. The piezoresistive investigations encompass the conventional application of foil gages applied to the tubing wall with adhesives and the application of gages by sputtering directly to the tubing wall. This latter technique is appealing because it eliminates potential problems associated with slipping, thermal expansion or delamination that can result from conventional applications of strain gages bonded to a surface. In the case of the fiber optics technique, an optically excited self-resonant microbeam forms the basis for the high-performance, low cost, fiber-optic strain sensors that uniquely combine silicon micro-fabrication technology with opto-electronic technology. These polysilicon micro-beams are sensitive strain transducers with nanostrain sensitivity, low thermal response (40 ppm/°C), and resonant frequencies in the Mhz range. Typical dimensions are comparable to the cores of multimode fibers, making the devices highly attractive, fiber-optic sensors. The optical excitation and sensing are electrically inert and impervious to cosmic radiation. The sensor-reflected modulated light is converted to a quasi-digitized electrical pulse stream by a photo detector and input into a counter.

Both of the proposed microtechnologies offer a very low mass, low power alternative to the pressure transducer. Furthermore, there are no radiation susceptibility concerns with the fiber optic application. The cost for these approaches appears to be comparable or possibly even cheaper than the conventional approach, and accuracy appears to be as good or better. Questions still needing to be answered are: 1) How difficult is the application process to the outer tubing wall, especially with smaller tube diameters representative of future generation S/C applications, and 2) How rugged is the installation process, taking into account normal handling loads, and S/C environmental loads (both on the ground and in flight)?

Optically Excited Self-Resonant Strain Transducers

Optically excited self-resonant micro-beams form the basis for a new class of versatile, high-performance, low cost fiber-optic sensors that uniquely combine silicon micro-fabrication technology with opto-electronic technology.

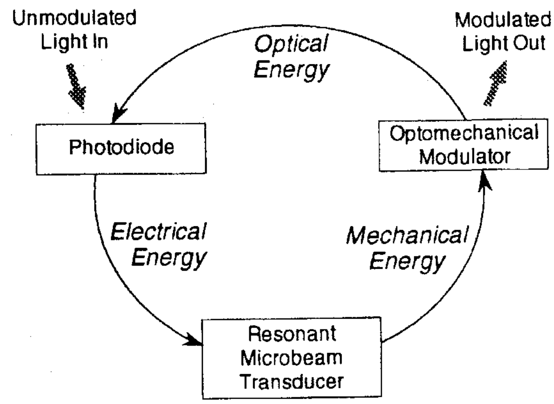

Figure 2 Optomechanical Oscillator

The vibrating microbeams utilize a unique gain mechanism involving the exchange of optical, electrical, and mechanical energy during each cycle of the oscillation, as shown in Figure 2. The simple structure is illustrated in Figure 3 where a microbeam is suspended in a polysilicon vacuum enclosure over a photovoltaic device to which it is ohmically connected.

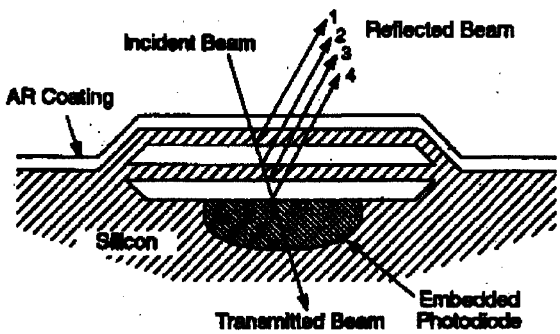

Figure 3. Cross Section of Optically Excited Self-Resonant Transducers

When irradiated with IR the photo-generated charge attracts and bends the microbeam toward the diode converting the electrostatic energy into mechanical energy. Movement of the microbeam alters the interference conditions for the light rays, modulating the transmitted light and hence the photovoltage sustaining oscillation of the high Q (100,000) by the absorbed

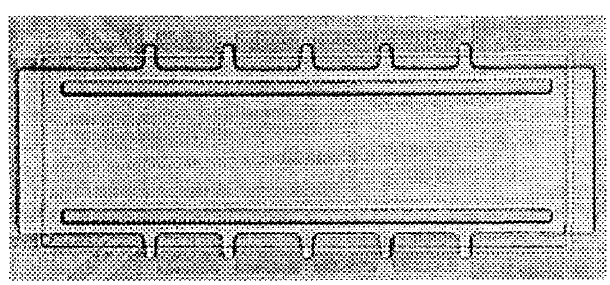

Fig 4 Optical Micrograph of Sealed Microbeam

optical energy (10^{-15} W). Highly modulated reflected light is produced by the Fabry-Perot interferometric structure composed of the microresonator and vacuum enclosure, allowing remote fiber optic excitation and readout of the microbeam resonant frequency for single point or multi-point sensing.

Typical dimensions are comparable to the cores of multimode fibers, making the devices highly attractive for fiber-optic sensors. The optical excitation and sensing are electrically inert and are impervious to atomic radiation. The modulation light is converted to a quasi-digitized electrical pulse stream by a photo detector and input to a counter.

Significant processing simplifications over electrical versions are realized by using optical methods. Self-resonant configurations eliminate external circuitry required to maintain the microbeam resonance, reducing system complexity and increasing reliability. Frequency modulated or quasi-digital output signals are readily interfaced with digital control systems (i.e. counter).

Figure 4 presents an optical micrograph of a sealed microbeam that is defined by the two long slits with dimensions of 200 x 46 μm (about 0.8 μm thick). A multimode fiber need be attached to the center of the silicon cover to provide the strain transducer.

In typical strain gage applications the Optical Resonant Beam Sensor (ORBS) is intimately coupled to a diaphragm or stress member which alters the tension in the beam and thus its frequency of resonance. The dynamic range of the ORBS is large (10^8) and thinning down the sensor housing increases the effective sensitivities of sensors.

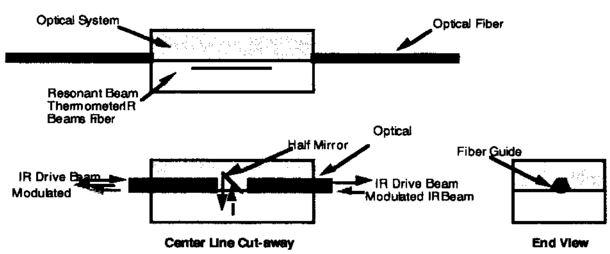

Figure 5. Resonant Beam Optics System

Figure 5 illustrates an optical network and coupler that is in development that will provide a robust optical fiber coupling to the ORBS which is of low bulk and simplifies the daisy-chaining of multiple ORBS.

Sensitive ORBS are cut from thin (~5 μm) pressure diaphragms in focused Reactive Ion Etching (RIE) machines and eutectically bonded to the outside of the tubes. An optocoupler unit is then 'optically' aligned over cavity and glued in place.

Foil gages

Bonded resistance foil strain gages were used to build a non-invasive pressure transducer on standard thin wall stainless steel and titanium tubing in sizes of 0.25, 0.375 and 0.50 inch outside diameter. One of the problems inherent in building a pressure transducer based on strain gaging the outside diameter of tubes is that the strain gages may produce output not only from the applied pressure, but due to bending, torsion, or axial loads that may be imposed on the tubes.

A design was developed to minimize the response to mechanically induced strains other than those produced by changes in pressure. Prototypes were gaged, a test set-up constructed, and tests conducted. The results of these tests indicated the feasibility of producing transducers with performance levels of 0.25 to 0.50%. Fittings were swaged onto several pieces of thin wall tubing of 300 series stainless steel per ASM 5560 and Titanium per ASM 4943. Measurement Group gages, Part Number N2A-06-S071P-350 manufactured from Lot Number A50AD584 foil with a gage factor of 2.10, were attached near the center of 9 inch long sections of tubes. This is a 350 ohm gage that has a grid that is 0.062 x 0.062 inches in size with a self temperature compensation of 6 ppm/F°. This was a compromise value based on availability. The ideal strain gage for stainless parts would have been gaged with a 9 ppm/F° gage and the titanium parts with a 4.5 ppm/F° gage. Such temperature compensated gages are less sensitive to the thermal transients.

In the basic configuration two strain gages were oriented at approximately 61.3 degrees to the tube axis (optimum angle of orientation is solely a function of Poisson's ratio for material) and wired into opposite arms of the Wheatstone Bridge (Figure 6.). This configuration results in strain levels of approximately83% of the hoop strain component with reduced sensitivity to bending or tortional strains.

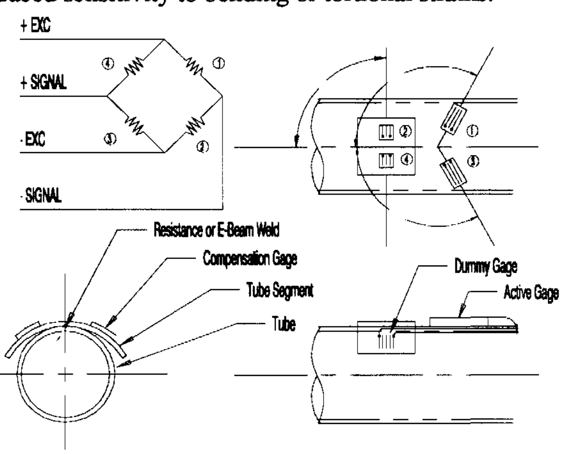

Figure 6 Bridge configuration

Gages were placed on stainless tubes of 0.25 inch diameter with 0.02 inch wall thickness, and 0.5 inch diameter with 0.035 inch wall thickness, and on titanium tubes of 0.25 inch diameter with 0.020 inch wall thickness and 0.375 diameter with 0.042 inch wall thickness. Gages oriented in the axial and hoop directions were also installed on the 0.5 inch diameter stainless tube.

Test Set-up

The test system consisted of an Enerpac hydraulic pump and a system of valves assembled to test the tubes over a 0-3000 psig range. Test pressure was set by comparison to a Teledyne Taber Model 206 Pressure Transducer with range of 0-3000 psig and a Beckman Industrial Meter Model 621 that had been calibrated in the JPL Standards Laboratory and found to exhibit maximum non-linearity and hysteresis errors of less than 0.1% (specifications are for 0.25%). Indicated test pressure could be set and controlled to within 1 psi of the desired reading and the strain gage bridges were completed with two precision 350 ohm gages that were matched to within 0.005%. A precision ratiometric A/D module was used as a read out for the pressure tube which had a non-linearity of 0.003% and with a test resolution of 0.01 microvolt/volt. The test set-up consisted of an angle iron frame on which the valves and tubing could be supported, with the tube in a horizontal position. Initially the reference transducer, a mechanical pressure gage, and a valve for purging the air from the system were placed down stream of the tubing. This hardware was supported off of the frame to keep the weight off of the tubing. This configuration caused problems due to mechanical loading and friction and was modified to move the reference transducer and mechanical pressure gage upstream of the tubing.

Test Results

Test results showed that typical maximum calibration curve errors of 0.5 to 1.0% could be achieved with the bridge completion resistors located remotely from the tubes. The errors were significantly influenced by transient thermal responses.

Configurations were then constructed that moved the bridge completion resistors to a small unstrained tube segment, fabricated from the same tube stock, and bonding the shim to the tube with RTV. The relatively soft RTV bond served to isolate the shim from strains in the tube. A further reduction in this response could be achieved by moving the bridge completion resistors to

Figure 7 Foil gages on 0.25" diameter titanium tube

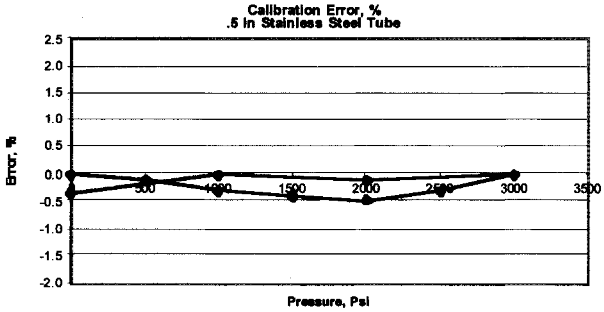

Figure 8 Foil gages on 0.05" diameter stainless tube

the tube itself with the penalty some loss of sensitivity and increased response to axial and bending strains.

Figures 8 and 9 present representative calibration test results obtained for these configurations indicating the feasibility of producing transducers with performance levels of 0.25 to 0.50%. Each figure consists of the calibration curve showing error from the terminal line constructed through the zero and maximum pressure points as a percent of full scale. Figure 8 shows results for the 0.5 inch stainless tube with 0.035 inch wall thickness configured with bridge completion resistors attached to a tube segment bonded to the tube. Figure 9 shows the performance improvement on the 0.375 inch diameter tube with 0.042 inch wall thickness resulting from completing the bridge with a pair of gages oriented axially on the tube. This configuration reduced the sensitivity to hoop strain by 27% and increases the sensitivity to bending or tension in the tube but reduced errors due to transient thermal response.

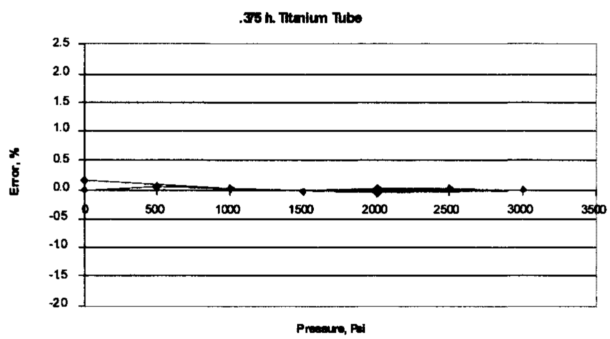

Figure 9 Foil gage on 0.375 dia. titanium tube

Thin Film Sensors

Standard thin wall stainless steel and titanium tubing in sizes of 0.25, 0.375 and 0.50 inch outside diameter were polished to a high degree prior to treatment. Tubes of both materials were fabricated with strain sensors using nickel-chromium thin film piezoresistive technology. As with the foil gage work, bridge completion gages were fabricated on tube segments of the same material and formed with a slightly larger diameter than the tube diameter. These segments were

Figure 10 Lithographic patterned piezoresistive gage

attached to the tubes after deposition and prior to final wiring (see Figure 6).

Figures 10 and 11 show thin film transducers produced by vendors using different patterning techniques. The relatively small radius of the tubes on which the thin films were placed presented manufacturing challenges. One vendor used a process in which an insulator material was deposited followed by photolithography to form the strain gage element pattern in the photoresist. The photoresist was removed and a new pattern for gold leads was placed on the parts. Gold lead outs were sputtered on and gold ribbons welded to the lead outs. An encapsulating insulator layer was sputtered over the gage. Figure 10 illustrates the geometry of a lithographic patterned gage. The second vendor used a process in which the strain sensitive layer was sputtered on as a continuous film and subsequently the strain gage grids were formed by means of laser cuts in the film (Figure 11). An

Figure 11 Laser ablated piezoresistive gage

encapsulating insulator was then sputtered on and selectively etched away in the gage tab areas. Wire bonds were then made to the strain sensitive elements. Parts were completed from 0.375 inch and 0.5 inch diameter tubes. No satisfactory parts were made using the 0.25 inch diameter tubes.

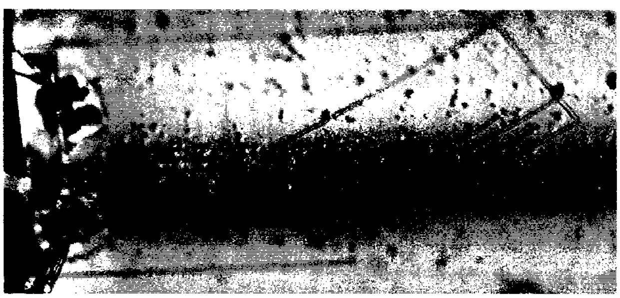

Figure 12 Pitting in surface of stainless tube

While all tubes were polished to a high degree prior to deposition significant pitting of surface remained, particularly for the stainless steel specimens. Figure 12, a micrograph of the surface of 0.5 inch diameter stainless steel tube, clearly illustrates the problem. This is a process issue that will be corrected by the

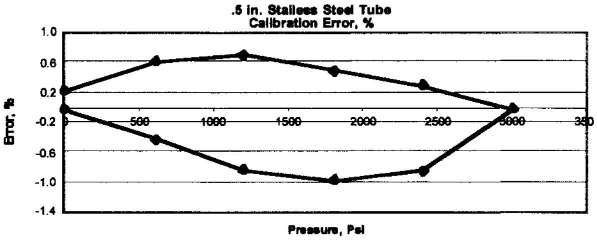

Figure 13 Calibration error 0.5" stainless tube

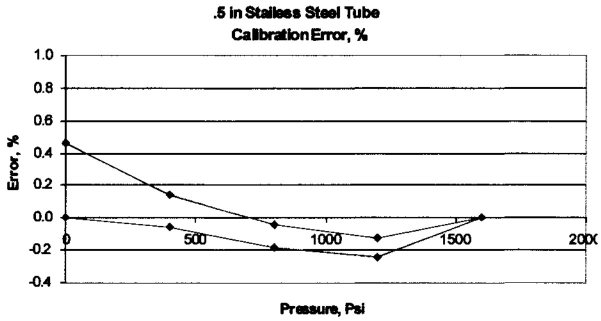

Figure 14 Calibration error 0.5" stainless tube

premachining of future parts. Some of the gage grids produced in the photolithography process were of good quality and some had significant defects. Better adherence to lithographic protocol will eliminate reoccurrence of this problem in the future.

One vendor fabricated a total of 15 parts, approximately five of each diameter. Initial yields looked favorable, but many parts were lost in the final step of attaching the lead wires to the gages. This appears to be caused by process problems related to excessive pressure in the wire bonding process.

Thin Film Test Results

Tests on parts supplied by each vendor included calibration, thermal zero response over a temperature range of -20 F° to 150 F°, individual gage apparent strain tests, electrical warm-up tests, and re-calibration following thermal cycling. Representative test results for laser ablated parts are shown in Figures 13-15. Test data showed that 3000 psi on the 0.020 wall stainless tubes resulted in strain levels that were too high for

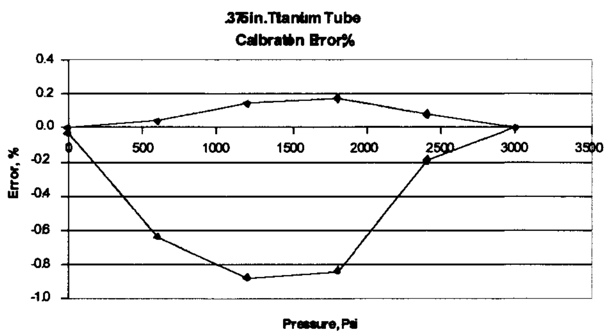

Figure 15 Calibration error 0.375" titanium tube

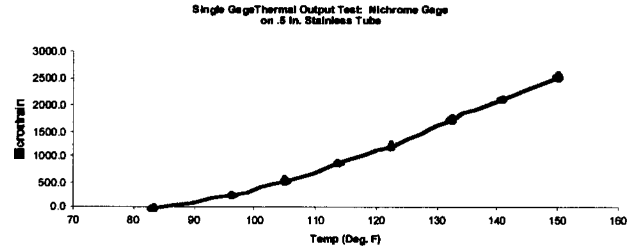

Figure 16 Thermal output for 0.5" stainless steel tube

good performance (Figure 13).

Lower errors were obtained when maximum pressures did not exceed 2000 psi (Figure 14). Figure 15 shows a typical calibration for the titanium 0.375 diameter 0.020 inch wall thickness tube tested to 3000 psi. At 3000 psi the operating stress level is approximately 75% of that in the 0.5 inch tubes and the titanium alloy has higher yield strength.

One of the results of the test program is that the deposited gages exhibited large resistance mismatches, with individual gages varying as much as 100 ohms from nominal values of 1000 ohms for one vendor and 1500 ohms for the other. This has implications on effective cancellation of undesired strain components and on the uncompensated thermal output. Another important result is the effect of the relatively high thermal output characteristics of the deposited gages compared to the foil gages. The resulting full bridge

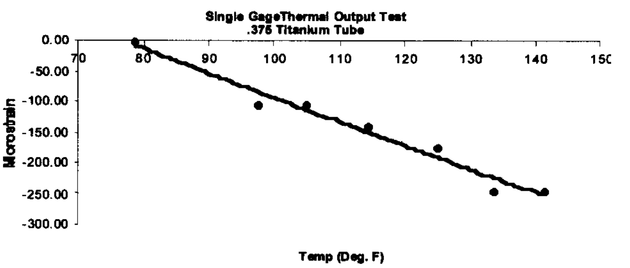

Figure 17 Thermal output for 0.375" titanium tube

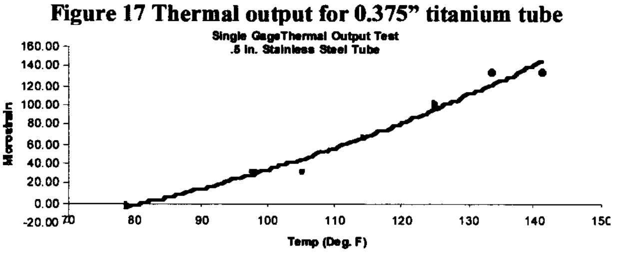

Figure 18 Thermal output for 0.5" stainless steel tube

thermal zero output change was high relative to typical bonded foil gage results. The deposition on the curved surfaces may have contributed to this problem. Figure 16 shows thermal output results for a single (lithographic patterned) gage from a 0.5 inch diameter stainless steel one vendor, which are extremely high. Figures 17 and 18 show thermal output results from stainless and titanium tubes from the other vendor which exhibites better behavior. Figures 19, 20, and 21 show full bridge thermal zero results. The major discontinuity in Figure 19 above 95 F° is unlikely to be a correct representation of the gage behavior, but is most likely related to poor resistive element definition on one of the compensating gages and a changed resistance path occurring due to thermal expansion of the substrate.

Testing was performed to measure the temperature change in the tubes as a function of pressure changes in the hydraulic system. It was found that a temperature change of approximately 1.5 F° occurred when the pressure was dropped from 3000 psig to 0 psig. This temperature change resulted in substantial transient zero shifts lasting for one to two minutes following the pressure change. Figure 22 shows the correlation between an RTD temperature measurement on the tube near the gages and the output change that occurs simultaneously. Curve shapes are remarkably similar and the figure lends support to the theory that transient

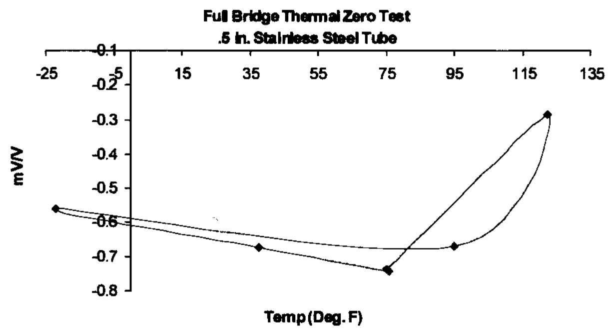

Figure 19 Full bridge thermal zero test 0.5" SS

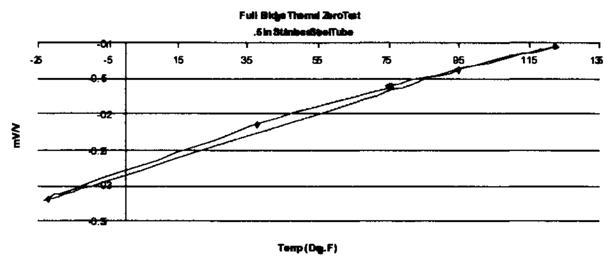

Figure 20 Full bridge thermal zero test 0.5" SS

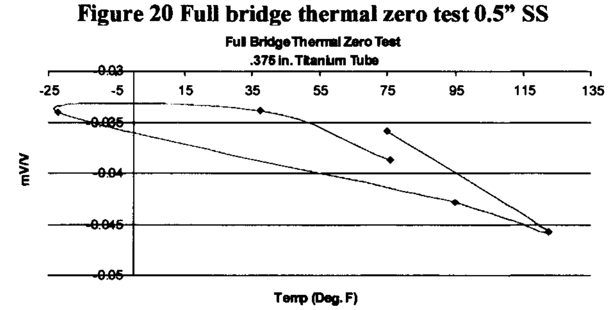

Figure 21 Full bridge thermal zero test 0.375" titanium

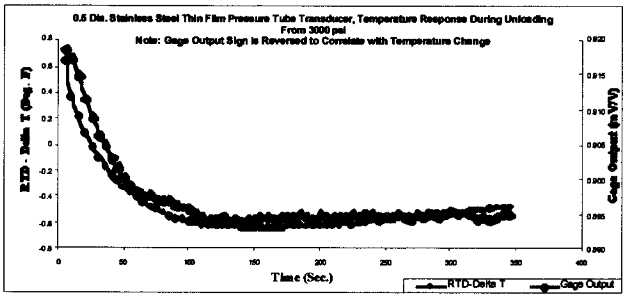

Figure 22Correlation between micro strain and temperature.

output is thermally related. This response was not well compensated by the bridge completion resistors since the thermal path to these gages was longer. One vendor's parts showed less effect than those from the other vendor, probably due to a combination of factors including differences in thermal output characteristics and differences in the attachment of the bridge completion resistor tube segments to the pressure tubes. The result was a phenomenon producing a significant effect on all parts and affecting calibration performance parameters as well as the zero return following loading.

A typical creep recovery test result, Figure 23, shows what appears to be an event governed by two time constants, one having a shorter time constant and greater magnitude which was due to the thermal effects and a smaller effect with longer time constant probably due to conventional creep mechanisms in the materials.

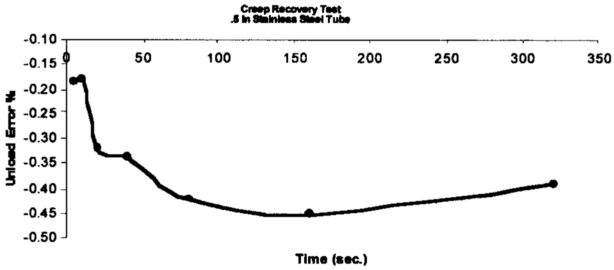

Figure 23 Creep test on 0.375" titanium tube

Conclusions

Test results on foil gages demonstrated that it is feasible to build a pressure transducer by gaging the outside of 0.25, 0.375 and 0.5 inch diameter tubing with performance levels of 0.25 to 0.5%.

Nickel-Chromium thin film gages were successfully deposited on tube diameters of 0.375 and 0.5 inches. These parts exhibited higher thermal outputs characteristics than the foil gage transducers. There is no simple means of reducing the thermal output of the deposited gages. However, minimizing gage self-heating by lowering excitation voltage, adopting pulsed excitation of short duty cycle, or using higher resistance gages will all reduce calibration disparities.

The variability demonstrated in the thin film gages may be related to uneven deposition on curved surfaces but more likely artifacts from pitted surfaces and faulty lithography. If the variation between gages on a single part could be reduced and thermal response times more closely matched, performance would be substantially improved to more closely match that of bonded foil gages.

Current efforts to produce working transducers using what has been learned to date involves machining tubes before polishing, correct lithographic procedures and lower pressure wire bonding. Also a modified flat surface design is under development that will result in compressive strains on the surface due to bending as well as tensile strains. This arrangement has the twofold benefit of producing differential strain in gages (tension and compression) and much closer thermal time constants between gages providing better cancellation of transient thermal errors within the bridge circuit.

As pressure measurements in propulsion applications are 'steady-state' thermal equilibration delays are not an issue; particularly as temperature (equilibrated) effects may be compensated for digitally. Thus thermally equilibrated parts performing to within a +/- 0.25% error band will be possible for fully optimized processes.

Acknowledgments

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